

Charge Generation and Collection from Heavy Ions and Protons

Introduction

Proton testing is much easier to implement compared to tests with heavy ions because protons have sufficient range to pass through semiconductor packages, eliminating the need to remove the package lid or “thin” the package by grinding. Protons produce single-event upset by via secondary interactions with the nucleus in the host material*. This process is compared with conventional single-event upset in Fig. 1. The cross section for proton interactions is much lower on a per particle basis because the probability of a nuclear interaction from the proton is on the order of 10^{-5} .

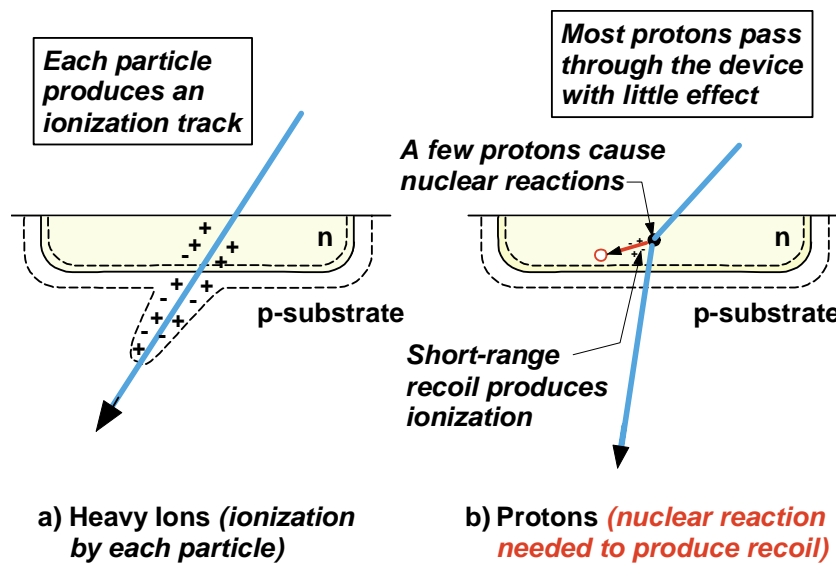


Fig. 1. Ionization from heavy ions and protons. The proton must first interact with a nucleus, producing a recoil atom with limited range that provides the ionization track.

When a beam of protons with fixed energy interacts with a target material (e.g., silicon), the recoils have a broad distribution of energies. This is shown in Fig. 2 for an incident beam of 62-MeV protons. The energy of the recoil atoms is plotted on the abscissa. Note that the number of recoils falls very sharply as the recoil energy increases. Several points should be noted. First, there are very few recoils with the maximum recoil energy, which is 8.4 MeV for primary particles with an energy of 62 MeV (except for rare events, which have extremely low probability). Second, the range of the recoil atoms is very short, typically $< 3 \mu\text{m}$. This means that only interactions that occur in close proximity to the sensitive region of the device will produce recoil atoms that contribute to upset. Third, the number of recoil atoms with energy = 4.2 MeV (1/2 the maximum recoil energy) is

*Protons also produce a weak charge track from direct ionization. However, the LET of direct ionization is so low that the process is negligible for nearly all microelectronic devices. For example, the LET of a 100-MeV proton is $0.006 \text{ MeV-cm}^2/\text{mg}$.

about 3×10^{-8} times lower than the number of primary particles. Consequently, it is necessary to use relatively high fluences of primary particles in order to measure upset, particularly if the upset threshold is above the midpoint recoil energy. This implies that we have very little chance of detecting an event with maximum recoil energy. Thus tests with protons usually represent recoil energies somewhat below the maximum recoil energy.

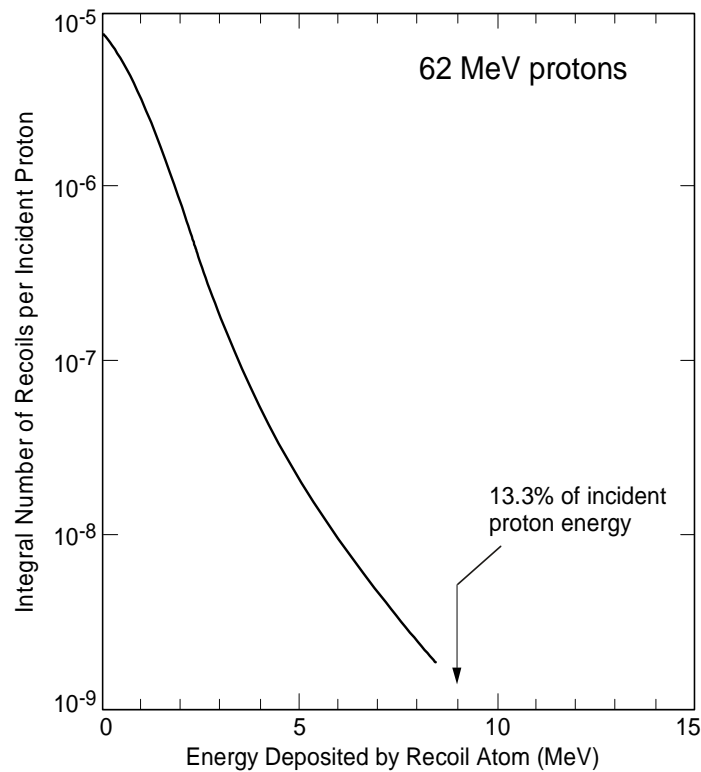


Fig. 2. Recoil energy distribution for a primary beam of 62-MeV protons.

The recoil energy distribution essentially scales with the energy of the primary proton beam. For silicon, the maximum recoil energy of a 186 MeV proton is about 12.6 MeV. Particles in space have a wide energy distribution, as shown in Fig. 3. Distributions are shown with various amounts of shielding, corresponding to a 705 km 98 ° inclination earth orbit. The number of protons falls abruptly at high energies, but there are still significant numbers of protons with energies ~ 500 MeV.

The mean proton energy is about 20 MeV for a 100-mil spherical aluminum shield, increasing to about 65 MeV for 400 mils. Examining this distribution, we see that tests with ~ 60 MeV protons are a good representation of the peak in the distribution. Tests with higher energies are necessary in order to address the effect of the more energetic protons in the spectrum, which are only slightly affected by shielding, but produce recoil atoms with higher energies.

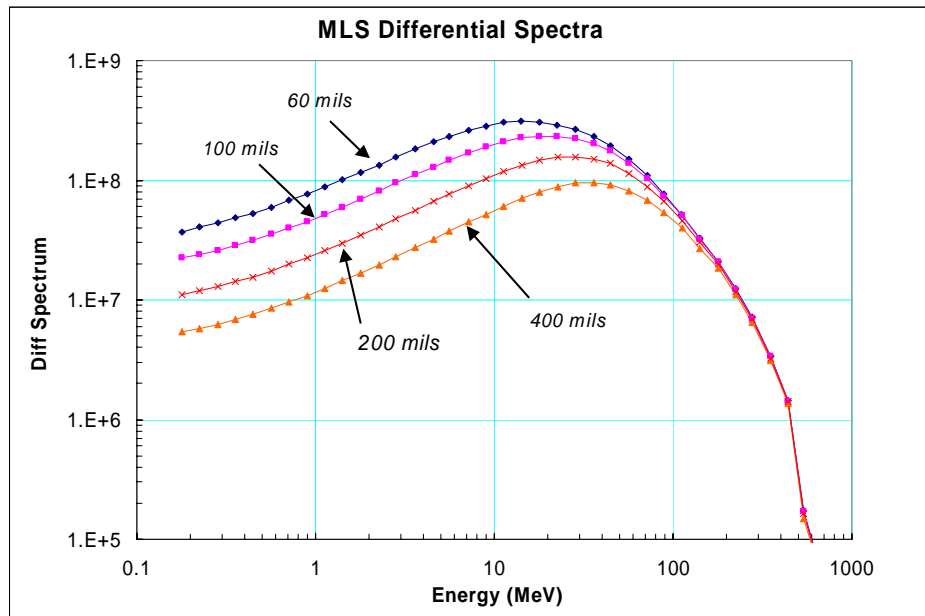


Fig. 3. Proton energy distribution for an earth-orbiting spacecraft.

Equivalent LET of Recoil Ions

In order to evaluate the effectiveness of proton tests relative to tests with heavy ions we need to know the effective LET of the recoil atoms. The LET of silicon recoils with various energies is shown in Fig. 4. The vertical lines show the maximum recoil for three different primary proton energies. Although this figure shows the maximum LET of the recoil atoms, it does not take the very short range of the recoils into account. When evaluating proton testing, we have to consider the total charge that is deposited in the sensitive region of the device by long-range primary particles and short-range recoils. The equivalence depends strongly on the properties of the device that is being tested.

CMOS devices are made with two basic types of substrates: lightly doped substrates, with constant doping level throughout; and so-called “epi” substrates, where the starting wafer is very heavily doped in order to provide a lower resistance. A thin epitaxial layer is grown on the top of the heavily doped region, and active devices are fabricated in that region. Fig. 5 compares these two types of construction.

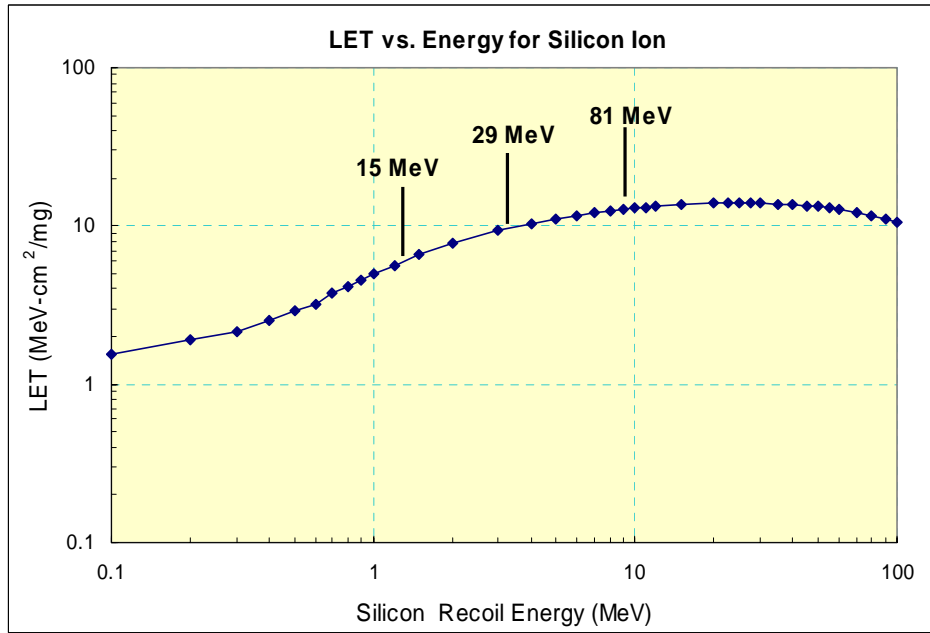


Fig. 4. Maximum LET of silicon recoil atoms vs. recoil energy.

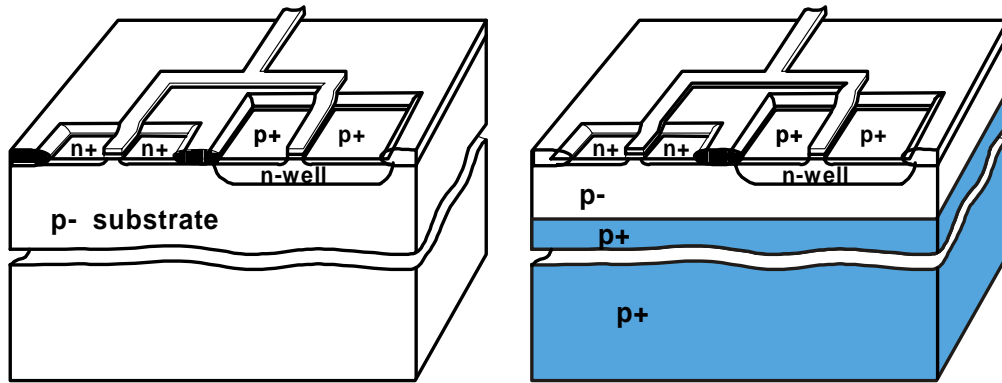


Fig. 5. Comparison of bulk and epitaxial wafers used in CMOS fabrication.

From the standpoint of charge collection, a bulk substrate can collect charge from deep within the substrate. Modeling studies have shown that this extends to more than 100 μm in p-substrates. In contrast, an epitaxial substrate effectively cuts off charge from the p+ layer, limiting charge collection to that of the thin epi layer at the surface. Although Fig. 5 shows a sharp transition between the p and p+ regions, boron from the p+ region diffused into the lightly doped p- region during processing, creating a transition region between the layers with intermediate doping. The effective thickness of the epitaxial layer ranges from about 2 μm for highly scaled CMOS to 6-8 μm for devices with feature size above 0.25 μm .

We can consider short-range recoils simply from the standpoint of deposited energy if they deposit all of their energy within the sensitive volume of a device, noting that 22.4 MeV of deposited energy in silicon corresponds to a total charge of 1 pC (assuming that nearly all of the energy goes into ionization). This can be used to calculate the equivalent LET for various substrate thicknesses. Table 1 shows the total charge generated in three different substrates by heavy ions and by the maximum recoil energy from 100-MeV protons. Equating charges, the effective LET of a proton test at 100 MeV is 4 MeV-cm²/mg for a bulk substrate, 8.6 MeV-cm²/mg for an epitaxial thickness of 7 μm, and 14 MeV-cm²/mg for a 2.5 μm substrate.

Table 1. Charge Collected in Three Basic Structures by Heavy Ions and Proton Recoils

Case	Structure	Heavy Ion		Proton Recoil (100 MeV primary)
		LET = 10 MeV-cm ² /mg	LET = 45 MeV-cm ² /mg	
1	Bulk substrate	1.5 pC	6.8 pC	0.6 pC
2	Epitaxial substrate (7 μm)	0.7 pC	3.15 pC	0.6 pC
3	Epitaxial substrate (2.5 μm)	0.25 pC	1.13 pC	0.4 pC

Thus, the effectiveness of a proton test depends on device construction. It is important to note that the effective LET is very low for devices with bulk substrates, providing little useful information about the sensitivity of a device to upset or latchup from heavy ions in space. Proton tests are more effective for devices on thin epitaxial substrates, but still do not adequately evaluate the response of a device to heavy ions in typical space environments.

For a system that operates at low altitude and low inclination – below 30 degrees – the heavy ion distribution does not extend above approximately 3 MeV-cm²/mg. Proton testing is a reasonable way to evaluate devices in that type of environment, which is typical of many space shuttle flights.

In addition to the equivalent charge produced by protons and heavy ions we also have to consider displacement damage. Proton tests require high fluences because of the small cross section, and displacement damage during testing can significantly change the response of a device, particularly for latchup.